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We showed that it is posible to cool atoms in a one dimensional optical lattice using to a novel degenerate sideband cooling technique. This method was then extended to a three dimension optical lattice. With this method, we are able capture all the atoms in a MOT and directly cool them to the photon recoil temperature at phase space densities of 1/500 using low powered (20 m W) diode laser beams. This represents a $2^{1/2}$ order of magnitude increase in phase space density over the best form of "grey" optical molasses.

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Stanford/Chu

End Report of AFOSR grant F49620-98-1-0219-P00005
Cooling and trapping of Atoms and Particles
(10/1/97 to 3/31/01)

1) Laser Cooling

During this granting period, we developed new methods to cool atoms. We showed that it is possible to cool atoms in a one dimensional optical lattice using to a novel degenerate sideband cooling technique.[i] This method was then extended to a three dimension optical lattice.[ii,iii] With this method, we are able capture all the atoms in a MOT and directly cool them to the photon recoil temperature at phase space densities of 1/500 using low powered (20 mW) diode laser beams. This represents a 2½ order of magnitude increase in phase space density over the best form of "grey" optical molasses. When used in conjunction with a far detuned trap, we were able to cool atoms to a phase space density of 1/30.

Since the atoms are cooled in an optical lattice, we can move the lattice with respect to the laboratory frame of reference by shifting the relative frequencies of the laser beams and launch the atoms in a cold atomic fountain. With this techniques, we were able to launch a meter high fountain with three dimension temperatures as low as 200 nK with an atom source brightness that is comparable to a BEC source of 5 millions atoms every 40 seconds.[iv]

We proposed a new method to cool atoms using stimulated scattering in an optical cavity.[v,vi] The moving atom modifies the field in a high finesse cavity, and the time delay of the cavity response creates a velocity dependent drag force on the atoms. Cooling close to the photon recoil limit is predicted. Because the light is de-tuned from form the atomic resonance, the detailed electronic structure of the atom is not important. Thus, molecules and even cluster can be cooled with this method.

Vladan Vuletic, my former postdoc and the principal inventor of this technique, was made an assistant professor at Stanford. He is now in the process of demonstrating this cooling method in his lab.

2) Collisions studies of Cs atoms

We discovered a low-magnetic field Feshbach resonance in the lowest energy ground state, $|F=3,m_F=3\rangle$.[vii] At our operating densities, we were able to study the collision properties in the hydrodynamic regime where the mean collision time is less than the oscillation time of the atoms in our trap. Other Feshbach resonances were discovered in the $|F=3,m_F= -3\rangle$ state.

Since virtually all collisions in this temperature range are s-wave collisions, the wavefunctions of all colliding atoms will be identical. We showed that radiative transitions from the collision state to an excited molecular state could be suppressed by up to a factor of 15 when the node of the ground state is tuned to the Condon point.[viii] This experiment led us to the discovery of host of extremely sharp collision resonances where loss of atoms from our trap were assisted by radiative transitions to unbound excited states. This represents a new technique in collision spectroscopy that allowed us to discover dozens of Feshbach resonances.[ix,x] Using our data, collaborators at NIST were able to determine the parameters for the singlet and triplet scattering potentials, the C_6 van der Waals coefficient, and the spin orbit coupling constant. These parameters allow us to determine the low

energy scattering properties of cesium.[xi] In particular, we now know the allowed regions of phase space where the Bose condensation of cesium is possible.

3) Atom interferometry

We published the results of an absolute atom interferometer measurement of the acceleration of gravity.[xii] This measurement represents an improvement in the absolute accuracy in atom interferometry by 5 orders of magnitude. The results can be summarized as follows: with the current apparatus, a precision $\Delta g/g \sim 10^{-10}$ has been achieved. The absolute accuracy is estimated to be on the order of ~3 ppb. In a side-by-side comparison with a gravimeter based on a Michelson optical interferometer where one of the arms is a falling corner cube reflector, we showed that our interferometer has ~4 times better signal to noise. Our quantum measurement of g also agrees with the macroscopic measurement to 7±7 ppb, thus eliminating a 20 year discrepancy that has existed between the neutron interferometer measurements of g and macroscopic measurements. In a long companion paper, we present an exhaustive study of the noise sources and analysis of the systematic effects of this measurement.[xiii] This work is relevant to all precision atom interferometer measurements.

We also presented a progress report of our $\hbar/M_{Cs}$ experiment.[xiv] This paper was presented just before we discovered how to eliminate a major systematic effect that had been plaguing the experiment for several years.

4) Calculations for an electric dipole moment search in cesium atoms trapped in a three dimensional optical lattice.

We proposed an experiment to measure the electric dipole moment in cesium. The atoms are trapped in a 3-D lattice trap where the atoms are effectively only exposed to purely linearly polarized light. An extensive calculations of possible systematic effects were given in the paper.[xv] Although the essential ingredients are now in place to begin this experiment, we have not yet mounted a concerted effort because of other opportunities that have arisen because of our cooling and collision work.

5) Other atomic physics work acknowledging AFOSR support includes the demonstration of Raman cooling in a blue-detuned trampoline trap that has achieved a phase space density of 1/20,[xvi] the publication of the a crucial part of our atomic fountain atom interferometer work, active vibration isolation system[xvii] low and the publication of the Nobel Prize Lecture in Physics.[xviii]

6) The study of polymer dynamics and biophysics with single molecules

Although not the central focus of the AFOSR grant, I include a brief summary of our work in polymer physics and biophysics. In 1989, we began a program to study the behavior of individual bio-molecules. This work introduced a revolutionary approach to studying polymer dynamics and biological processes, one molecule at a time.

The most significant work during this granting period was our discovery that identical molecules placed in an identical flow field will stretch to a new equilibrium state along several different pathways.[xix] This so-called "molecular individualism" has caused a paradigm shift in our

thinking of both polymer physics and biology. Previous to this type of work, virtually all of our knowledge in chemistry and biology has been discerned from experiments that have measured the properties of a large ensemble of molecules. This experiment graphically showed that the average behavior of many molecules could obscure the true behavior and lead one to erroneous conclusions.

We also were able to measure changes in the molecular configurations of polymers in solution and quantitatively link these changes, for the first time, to the bulk rheological properties of polymer solutions.[xx,xxi] Other polymer work is also listed below.[xxii]

We have also continued a program that studies behavior of biological processes that we began with the study of molecular motors using optical tweezers.[xxiii]

During this granting period, we reported first demonstration that fluorescence energy transfer (FRET) can be used to track the motion of a single immobilized molecule undergoing conformational changes.[xxiv,xxv] Using a RNA junction taken from the small sub-unit of the ribosome, we observe the conformational changes that occur when a protein or Mg^{2+} binds to the junction vertex. Under rapid buffer exchange of Mg^{2+} ions, the induced motion produced FRET changes that were in good agreement with the calculated values.

We reported the catalysis and folding individual Tetrahymena ribozyme molecules using fluorescence microscopy.[xxvi] The dye-labeled and surface-immobilized ribozymes used were shown to be functionally indistinguishable from the unmodified ribozyme free in solution. This work establishes single molecule fluorescence as a powerful tool for examining enzyme folding, and led to the discovery of new intermediate folding states and multiple folding pathways.

We published the first study of single molecule protein folding, using fluorescence quenching as the local probe of molecular motion.[xxvii]

7) Talks

Many endowed lectures, plenary and invited talks were given at universities and conferences during this granting period, by either the principal investigator or his students and postdocs.

8) Patents

There was one patent filed as a result of work done during this granting period for the laser cooling of atoms and molecules in an optical cavity.

9) Student and Post-doctoral training during this granting period

During this granting period, Achim Peters graduated and accepted a position at the University of Konstanz. There he completed his Habilitation degree under Jurgen Mlynek. Doug Smith graduated and is completing a post-doc position in Carlos Bustamante's group in Berkeley. He will begin as an Assistant Professor at the University of California, San Diego in the fall of 2001. A former graduate student, Tom Perkins will begin as a professor at JILA/University of Colorado in the fall of 2001. While a student with me, Tom won the Padden Award of the APS for the best thesis in polymer science. He currently has a Burroughs-Wellcome Career Development Award. Joel Hensley, Keng-Yeow Chung, Hazen Babcock, Andrew Kerman and Cheng Chin are expected to graduate in the summer of 2001. Keng-Yeow Chung, Andrew Kerman will stay on as short term postdocs in order to complete experiments beyond their thesis work.

Taekjip Ha, a former post-doc, began as an Assistant Professor at the University of Illinois, Urbana, in September, 2000. Tj Ha won a Biophysical Society Prize for his work in single molecule

fluorescence resonance energy transfer (FRET). Xiaowei Zhuang, came to Stanford as a Marvin Chodorow Fellow and was later awarded a NIH Career Development Award. She will begin as an Assistant Professor at Harvard in the fall of 2001. Andreas Wicht, a Humboldt Fellow, will have completed his postdoctoral term as well and has a position return to Germany.

An undergraduate, Aparna Bhatnagar, completed her honor's thesis and is now a graduate student at Stanford. Ania Blesynski, another undergraduate honor student in my lab, started as a graduate student in Harvard.

All of my graduate students and postdocs since the beginning of my career as a principle investigator are employed as research scientists. They include tenured professors at U. of Penn (Arjun Yodh), U. of Tokyo (Takahiro Kuga), Strathclyde (Erling Riis), Yale (Mark Kasevich), Weizmann Institute (Nir Davidson), Caltech (Steve Quake). David Weiss and Kurt Gibble are about to accept tenured offers. A former postdoc (Leo Hollberg) is a group leader at NIST, and a former graduate student (Michale Fee) is a biophysics researcher at Lucent Technologies. Two other undergraduates who have done honors thesis with me are now tenured at Cal Tech (Steve Quake) and about to be tenured at Stanford (Kam Moler). A third undergraduate (Andreas Vasy) in year long reading class with me is an assistant professor of mathematics at Berkeley. My former technician at Bell Laboratories (Alex Cable) is the founder and owner of Thor Labs, a major optical components company. Wayne Volkmuth is a research scientist at Incyte Pharmaceuticals.

8) Awards

In addition to the prizes earned by member of the Chu group listed above, S. Chu was awarded the Nobel Prize in Physics in 1997. He was also elected to the American Philosophical Society, a fellow the AAAS, foreign member of the Chinese Academy of Sciences and the Korean Academy of Sciences and Technology.

9) Women in physics

Five female undergraduate students completed their honors thesis with my group. Three of them are currently physics graduate students at Harvard. Kam Moler, a earlier honors thesis student, will be tenured early in the Applied Physics Department at Stanford.

There are currently two female graduate students and one female postdoc (Xiaowei Zhuang, soon to begin as an Assistant Professor at Harvard) are now working in my lab. A female graduate student, visiting from the University of Strasbourg, spent one summer in my lab.

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